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# Advanced Lithium Ion Systems for Military Vehicle Applications

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## Abstract:

Li-ion is a relatively new battery technology that has been commercialized within the past 15 years for the portable electronics industry. Work has been undertaken to explore the high power capability of this technology. The results show that Li-Ion rechargeable products are capable of providing very high rate capability. Saft has developed a family of products that specifically address the electrical power requirements for manned and unmanned military vehicle applications. Saft's Li-Ion battery technology offers a broad range of capabilities to provide stored energy for applications requiring Silent Watch and power for Silent Mobility and advanced Hybrid Electric Propulsion.

## Introduction

The higher energy and power density of Li-Ion battery technology offers a significant reduction in the weight and volume for HEV battery system compared to lead acid and nickel metal hydride technologies. Saft's High Power Li-ion battery technology has demonstrated specific power of over 6,000 W/kg under continuous discharge and a pulse discharge of 8,000 to 12,000 W/kg. Results of Saft's High Power and Very High Power Cell technology will be shown, in addition to recent applications of LiFePO<sub>4</sub> materials into Saft's High Power cell designs.

## High Power Cell Technology

Saft has been developing high power battery systems for military and automotive applications for the past 10 years. This High Power Battery Technology has been steadily improved as advances in electrochemistry are proven and implemented. The VL34P cell was recently developed to provide the ideal dual performance of power and energy suited for military vehicle applications. This cell has been used in series hybrid applications to support battery only operation, silent watch and drive assist. The performance characteristics of the cell make it an ideal candidate for integration into battery systems for hybrid electric drive vehicles.

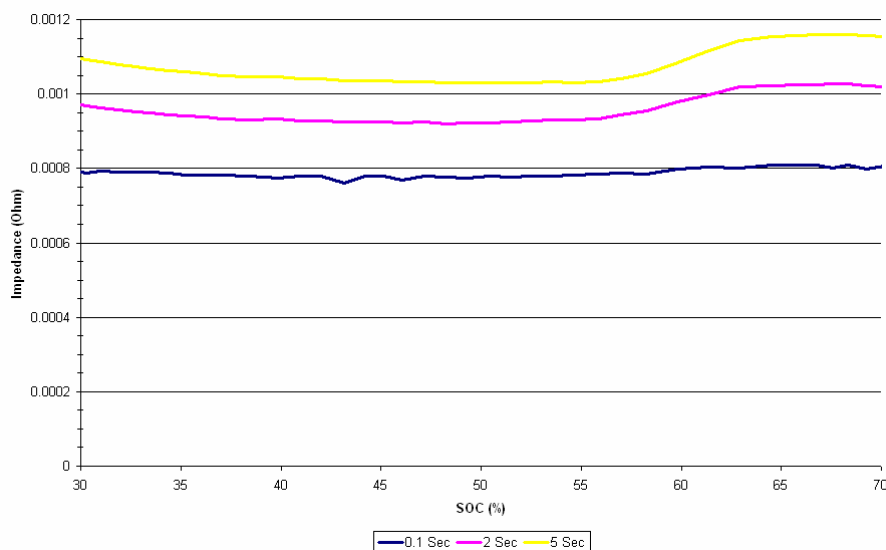
The cell incorporates improvements in many aspects of the cell design. The electrochemical design has been updated to improve the performance of the cell for high rates and low temperatures. It has been repackaged to improve the volumetric and gravimetric power and energy densities, while moving to lower cost components and processes. Improved packaging and assembly methods have also allowed for a significant reduction in the internal resistance of the cell, resulting in improved power, improved energy, and lower heat generation. This allows for a uniform temperature distribution within the cell and a means of effectively removing heat from the cell to improve cell life. The following table is a summary of the performance characteristics of the VL34P Li-Ion cell.

**Table I – VL34P Performance Characteristics**

	Units	Value
Mass	kg	0.94
Volume	L	0.41
Charge Voltage	V	4.1
Nominal Capacity	Ah	33
Specific Energy	Wh/kg	120
Energy Density	Wh/dm <sup>3</sup>	280
Terminal-to-Terminal Length	mm	184
Max Discharge Current @ 25°C - Continuous	A	500
Max Discharge Current @ 25°C – 2 sec pulse	A	1900
1kHz AC Impedance	mΩ	0.45

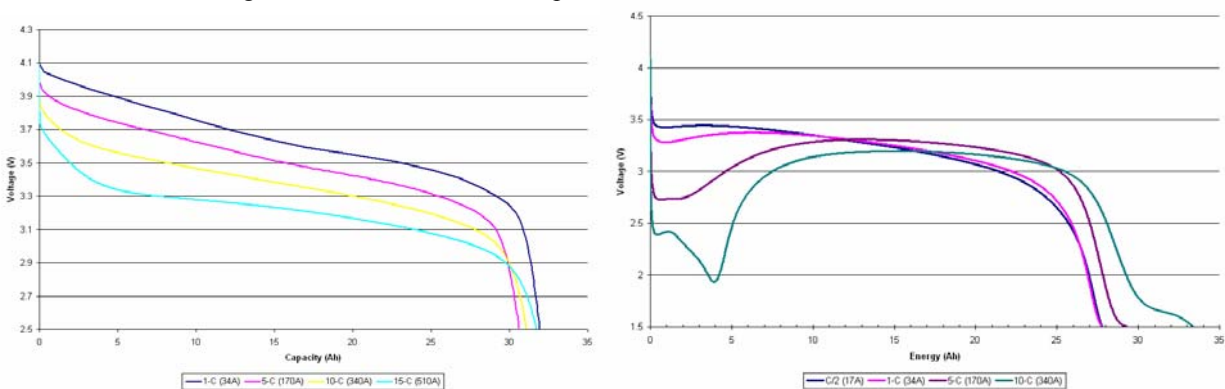
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Testing was performed on the VL34P cell to characterize the cell's internal resistance over the typical state of charge range. This was accomplished by doing a series of 6-second, 200A discharges with appropriate rests between pulses for stabilization of cell temperature. Figure 1 Shows the results of this testing. The uniform low resistance over SOC is ideal for hybrid vehicle type applications that operate in the 30-70% SOC range.



**Figure 1 –VL34P Cell Internal Resistance versus SOC**

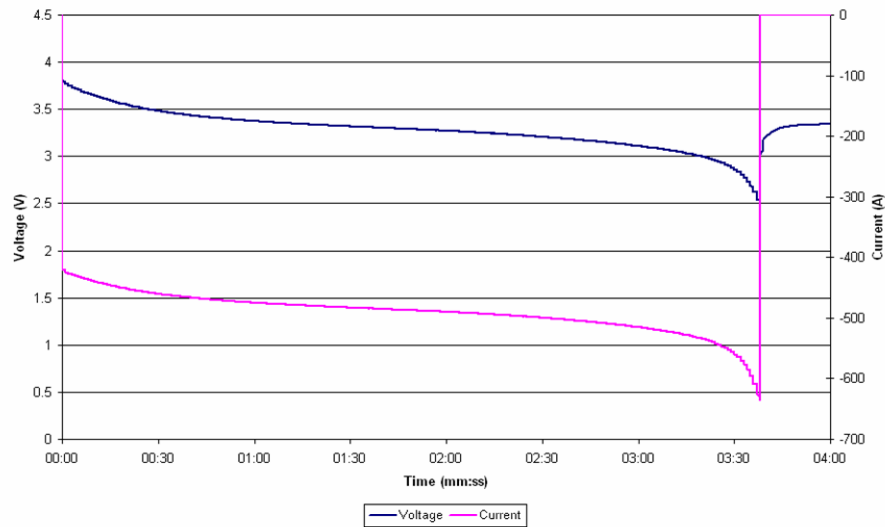
**VL34P Rate Performance** - The VL34P cell was discharged at various rates while at 25°C and -30°C in order to observe its performance. The results confirm the excellent rate capability of the cell. The cell can support a 510A constant current discharge and still deliver the full capacity of the cell. Figure 2 shows the results of the testing.



**Figure 2 – VL34P Constant Current Rate Capability @ Room Temperature and at -30°C**

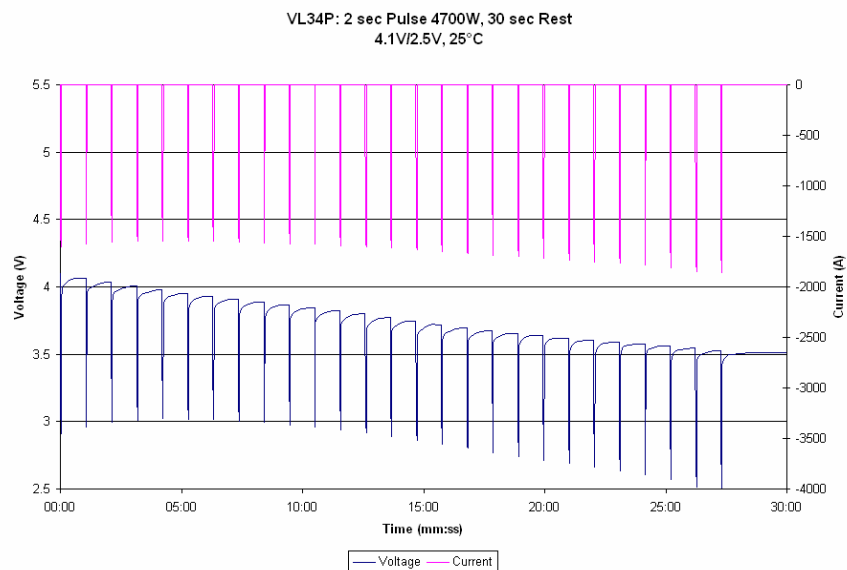
Also shown is a similar series of constant current discharge tests at -30°C. The excellent cold temperature performance of the cell is shown with 85% of the cell capacity delivered at C rate discharges at -30°C.

Further testing was performed to quantify max deliverable power from the cell. A continuous constant power discharge was applied to the VL34P cell. The cell, maintained at 25°C, was discharged from 4.1V to 2.5V at a rate of 1.6 kW. The discharge lasted 218 seconds before hitting the lower voltage limit. The average discharge current was 490A with 29.7 A-hr removed. Details from this discharge can be seen in Figure 3.



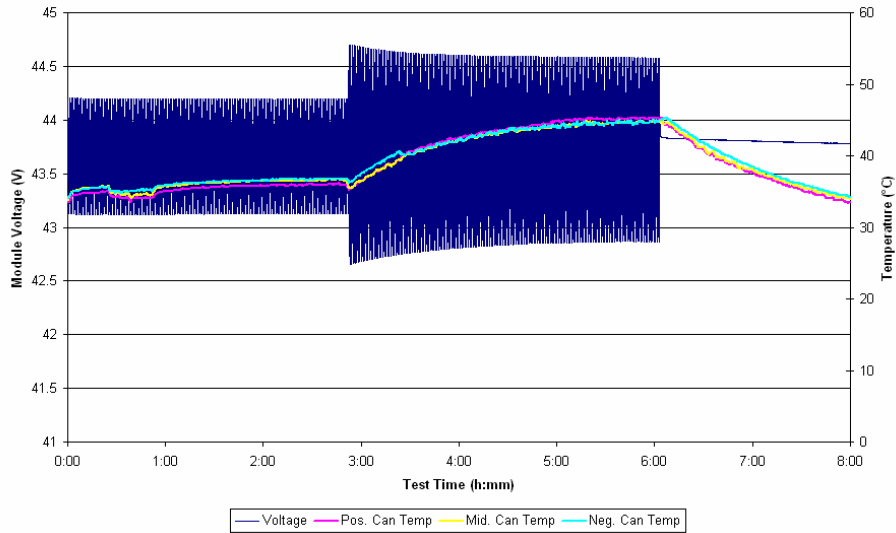
**Figure 3 - VL34P 1.6kW Constant Power Rate Capability @ -30°C**

**VL34P Pulse Discharge Power** - Pulse testing was performed on the VL34P. 4.7 kW constant power pulses were applied to the cell for 2 seconds, followed by 30 second rests. These pulses were continued from an initial full state of charge (4.1V) to a 2.5V cutoff. Twenty six (26) pulses were completed, with the twenty seventh pulse lasting for 1.8 seconds before hitting the lower voltage limit. The average discharge current during the pulse chain was 1,350 A, with the minimum current 1,150 A, and a peak current of 1,850 A. Over 23 A-hrs of energy was discharged from the cell during the pulse series, again confirming the high rate capability of this cell. The results are shown in Figure 4 below.



**Figure 4 - VL34P 4.7kW 2 sec Pulse Discharge Power**

**VL34P Module Testing** - In order to fully evaluate the VL34P cell, testing was done at the module level to quantify the heat generation during cycling. Testing was done in ambient air at 28°C with no forced air cooling, only natural convection. Various tests were run on the VL34P modules. Thermocouples were attached to the cells in the modules to fully evaluate the cell temperatures at various locations. Figure 5 shows results from cycling the VL34P module. The initial testing was run at a constant current cycle of 50A for 3 hours. The cycling was performed around 50% SOC with a 30sec charge and 30 sec discharge. The temperature for the cycling at 50A stabilized at 37°C. This testing was immediately followed by cycling at 100A for three hours under the same conditions. The temperature for the cycling at 100A stabilized at 45°C.



**Figure 5 - VL34P Module Cycling: 50A Cycling followed by 100A Cycling**

Overall results of this testing show that the lower cell internal resistance results in less heat generation rates that can be easily managed with simple cooling methods. The same testing profiles were run on Saft's Gen1 vehicle module using the VL30P cell configuration to compare the results and quantify the cell improvements.

**Heat Generation** - The constant current cycling was used to monitor heat-rise within the module, as well as to determine the heat generated within the module during cycling. The heat generation rate was deduced by analyzing relative difference between charge and discharge power. This data, along with maximum temperature data, has been placed in the Table below. The improved design of the VL34P cell results in significant reduction in heat generation in the module. This allows for easier management of heat at the system level.

**Table II – Constant Current RMS Average Cycling Results**

		VL30P	VL34P	VL30P	VL34P	VL30P	VL34P
		50A RMS		*100A RMS		150A RMS	
Max Temps	Pos. Can	36.1°C	36.1°C	47.9°C	45.4°C	**	50.3°C
	Mid. Can	35.8°C	36.7°C	47.6°C	45.0°C		51.1°C
	Neg. Can	36.0°C	36.9°C	49.8°C	45.3°C		50.7°C
	Core	38.1°C	N/A	55.0°C	N/A		N/A
Power	Charge	2185W	2202W	4427W	4437W	6738W	6699W
	Discharge	2122W	2163W	4198W	4305W	6211W	6413W
	Heat Generation	63.2W	39.5W	229.2W	131.9W	527.6W	286.2W

Notes:

\*Side Covers Removed

\*\*Did not reach Steady State, hit 55°C Limit

### Saft's High power Battery Systems

Saft has gained valuable experience with implementation of battery systems in a number of vehicle applications. Saft has delivered several systems with fully integrated control electronics. Such battery controllers are used to monitor the individual cells and maintain the battery in a usable operating window. Besides the monitoring feature of the control electronics, the integrated controller includes such items as precharge, cell balancing, and contactors in one plug and play package for integration into a vehicle. In addition, the system also reports battery status and provides feedback control of allowable charge and discharge currents based upon, temperature, SOC, and prior usage conditions.

### Iron Phosphate and Saft's VL-V Power Technology

The LiFePO<sub>4</sub> chemistry is interesting for certain applications, as the improved thermal stability of the LiFePO<sub>4</sub> design allows for even more tolerance to extreme abuse conditions. Recent advances in processing techniques have allowed Saft to apply this technology into the large format high power cells. Saft has been working with Phostech & Sud Chemie, a licensed supplier of LiFePO<sub>4</sub>, for developing this product line.

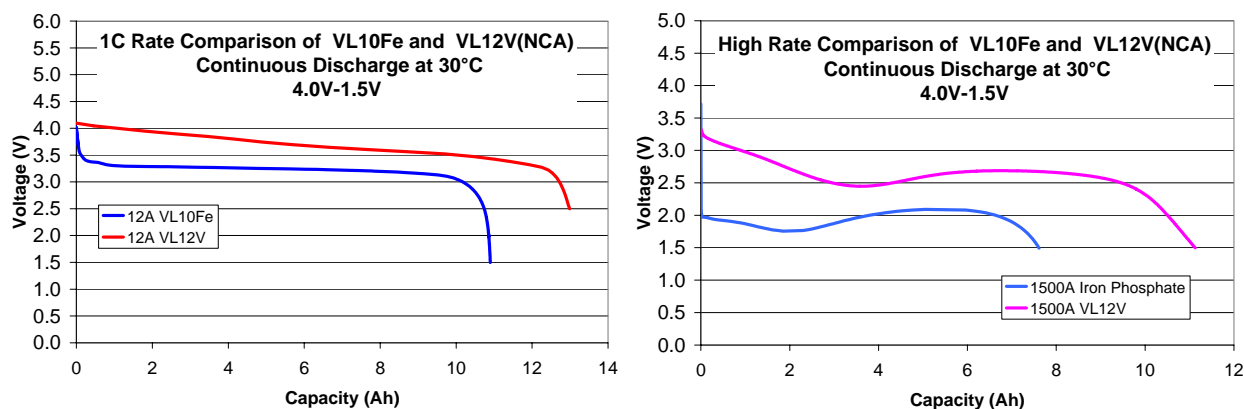
Saft initiated its work into the LiFePO<sub>4</sub> chemistry under a research program with Army Research Lab. With the help of ARL, Saft was able to successfully develop a high power cell design that incorporated Saft's high power electrochemistry and ARL's advanced electrolytes for cycle and calendar life improvements. Since that time, further IR&D has allowed for continued development of the technology and put in place advanced processing techniques to make the chemistry a viable candidate for certain applications.

Saft has successfully developed a very high power LiFePO<sub>4</sub> cell using the standard VL12V NCA cell design as a baseline. Table III compares the performance characteristics of the two cells.

**Table III – Comparison of VL12V and VL10Fe cell performance**

Cell	VL10Fe	VL12V
Cathode	LiFePO <sub>4</sub>	NCA
Nominal Voltage (V)	3.3	3.6
Nominal Capacity at C rate (Ah)	10	12
V = f(SOC) at 50% DoD at C rate (mV/SOC%)	0.13	0.66
Maximum Discharge Current at 25°C (A)		
Continuous	1500	1500
2s Pulse	1700	2200
200ms pulse	2200	3200
Specific Energy (W/L)	54	74
Energy Density (Wh/L)	128	175
Specific Power at 25°C 100% SOC (W/kg)		
Continuous	4375	4600
2s Pulse	5000	6800
200ms Pulse	6400	10,000

For consideration of this chemistry as a suitable candidate for military applications the high power capability, the ability to operate from -40°C to 72°C, and the stability of the cell resistance over calendar life and temperature cycling must be evaluated.



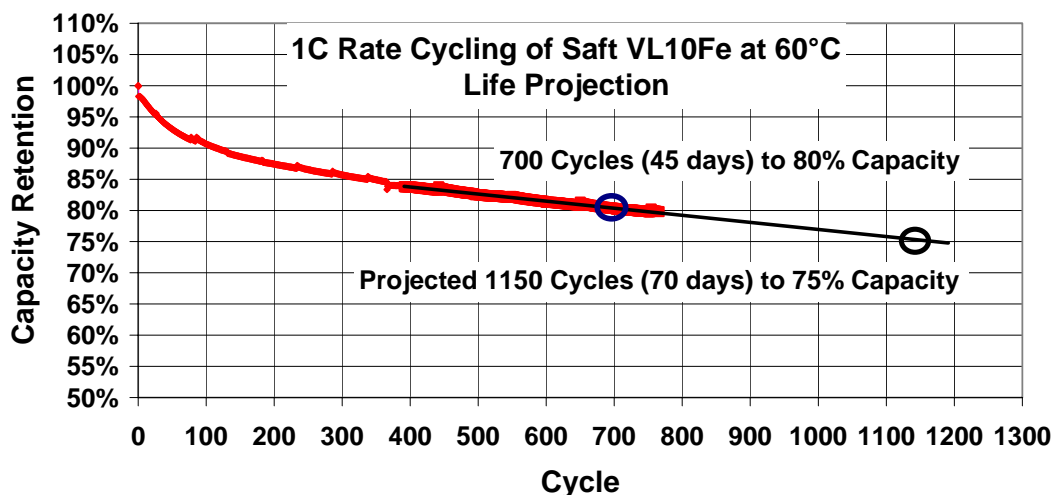
**Figure 6 - VL12V and VL10Fe Rate Capability Comparison @ 30°C**

Figure 6 shows the comparison in rate capability between the two cell designs. At a Discharge current of 12A from full SOC, the Iron phosphate cell is capable of delivering 75% of the energy of the NCA cell. At 1,500A, the Iron Phosphate cell can only deliver 50% of the energy of the NCA cell. The main reason for this difference is the lower operating voltage of the LiFePO<sub>4</sub> active material.

**VL10Fe Pulse Power** - In addition to the constant current or constant power discharges, further characterization was performed on the VL10Fe cell for pulse power. The cell was subjected to pulse discharges at 1,750A for 5

seconds. The resulting power delivered from the cell over that time is 5,400 W/kg. This confirms that the VL10Fe is the 2<sup>nd</sup> post powerful cell after Saft VL-V NCA chemistry..

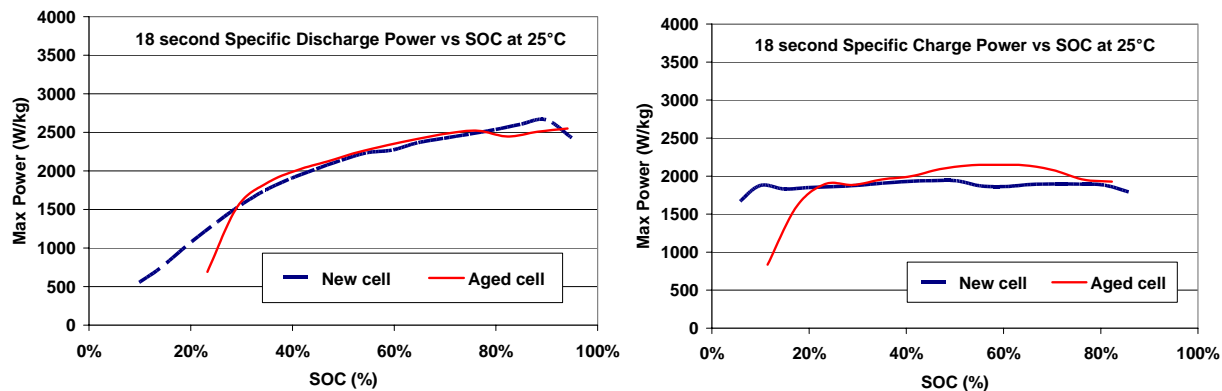
**VL10Fe Cycle Life and Aging** – Understanding the cycle life and the effect different storage conditions is essential for successful implementation in a vehicle applications. Some preliminary data has been generated to quantify the performance of the LiFePO4 VL10Fe cells.



**Figure 7 - VL10Fe Cycling at 60°C**

The above figure shows the capacity fade from cycling at 60°C. From this result, it is projected that 1150 cycles will be obtained before 25% capacity loss. High temperature operation significantly reduces the life of the LiFePO4 cells. Calendar life testing is incomplete but initial results indicate a shortened life from exposure to elevated temperature, similar to other Iron Phosphate cells.

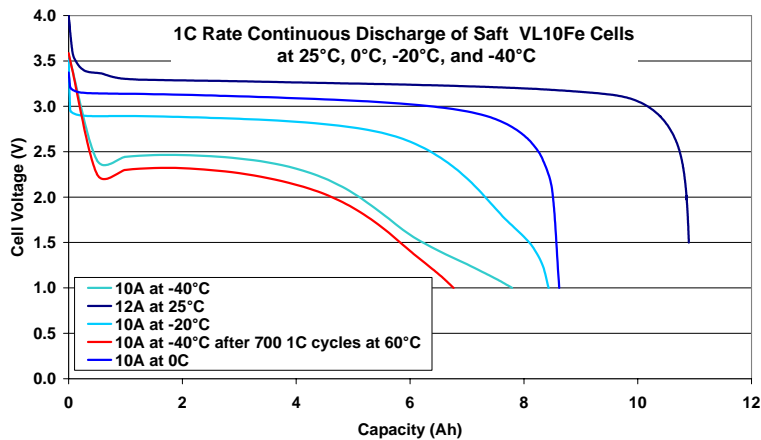
The effect of the aging on pulse power performance was also quantified through testing. The pulse power was measured during the capacity fade test to quantify any shift in resistance as a result of the cycling. The power was measured at 2500 W/kg 18sec @ (70-100)% SOC & 25°C for discharge and 1900 W/kg 18sec @ (20-80)% SOC & 25° C for Charge. Results of this testing are summarized in Figure 8.



**Figure 8 - VL10Fe Power**

The result of this testing show that Saft's VL10Fe LiFePO4 cell impedance is very stable for charge and discharge power over the life of the cell. Essentially no degradation is seen in power in the typical SOC window for hybrid vehicle applications.

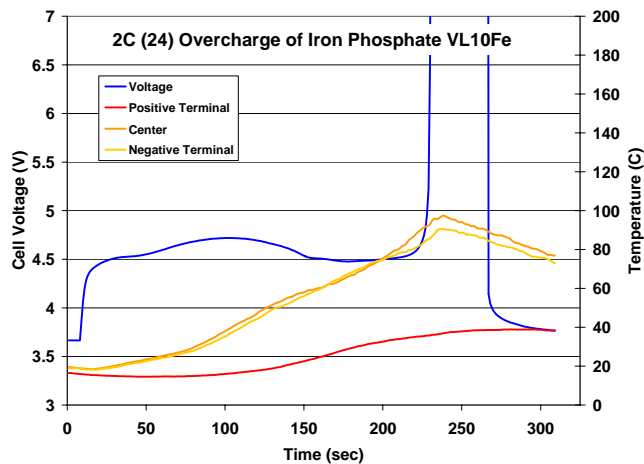
**VL10Fe Cold Temperature Performance** – The rate capability of the LiFePO4 chemistry was also examined at cold temperature. The cell was subjected to 1C discharge rates at various temperatures. The results of the cold temperature discharge show promise for achieving the same levels as are seen with the Saft VL-V chemistry.



**Figure 9 - VL10Fe Cold Temperature Performance**

**VL10Fe Abuse Tolerance** – The main reason for interest in the LiFePO<sub>4</sub> chemistry is the improvement in stability of the active material to extreme abuse conditions. The reason that the stability is improved is that the LiFePO<sub>4</sub> material has less lithium excess and lower specific energy. During overcharge and other abuse conditions, this results in lower temperature rise in the cell and less energetic ‘events’.

The improved tolerance to overcharge was confirmed with the VL10Fe cells. A 2C (24A) charge was applied until the cell was in overcharge condition. The cell vented with no smoke or fire and showed a cell skin temperature less than 100°C.



**Figure 10 - VL10Fe Cell Overcharge Testing**

Overall, the material is less energetic than other Li-Ion materials, but at the cost of lower power and energy performance. Saft is currently investigating a VL34P format cell with LiFePO<sub>4</sub>, under the ManTech program with TARDEC, to confirm the high abuse tolerance of the chemistry in the large format cells with higher energy.

#### **System level Comparison for Iron Phosphate**

The lower operating voltage and energy density of the iron Phosphate technology must be taken into consideration at the system level to ensure adequate performance of the vehicle. In order to achieve the same performance targets for power and energy, additional cells are required for the system. Using a 350V nominal voltage as a baseline for a vehicle application, a system made with iron phosphate cells would require one extra 12 cell module, or 12.5% more cells, to achieve the same system operating voltage. The extra module will also add additional energy and power capability to bring the Iron phosphate system close to the performance of the NCA system. This additional

module adds weight and volume, adversely affecting the power and energy densities. Table IV summarizes the system level comparison for NCA versus LiFePO4 vehicle battery.

**Table IV – NCA & LiFePO4 System level Comparison for 350V Vehicle Battery System**

		NCA	LiFePO4
# of Cells		96	108
Capacity	Ah	34	30
Energy	kWh	11.8	10.7
Weight	kg	150	170
Volume	L	105	120

### **Conclusions**

Saft's VL34P cell has been shown to be well suited for use in military vehicle applications. The high power of the cell is able to support the charge and discharge power profiles of hybrid vehicles. The low cell resistance allows for simple cooling methodologies for the modules and batteries.

Saft's implementation of controls in the battery systems for vehicles provide an excellent means of effectively monitoring and integrating the battery within the vehicle controller.

Iron Phosphate is suitable for high power applications that require an added level of redundant safety to extreme abuse. The requirements of the application must be considered as there are tradeoffs in lower power & energy, poorer low temperature performance, less stability at high temperature for storage.

Overall, Saft's cell and battery design provide for ideal solutions for vehicle applications. The current efforts underway for cost reduction of these products, led by Gus Khalil at TARDEC, will further help make these products suitable for the military vehicle market.

### **Conclusions**

*Saft would like to thank Gus Khalil, Henry Catherino, and Sonya Gargies at US Army TARDEC for continued support of ongoing developmental efforts under the ManTech program. Saft would also like to thank Dr. Richard Jow of ARL for his continued guidance and support and insight into new materials and performance improvements. Lastly, Saft would like to thank our customers for continued feedback of the systems installed in their demonstrator vehicles. This insight allows us to continually update and improve the products for the vehicle market.*

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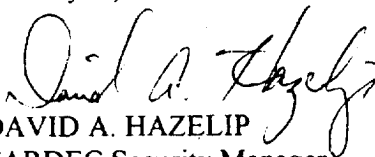
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